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Modelling the residual N effect of slurry applied to maize land on dairy farms in The Netherlands

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Abstract

Quantification of the residual N effect of manuring is required to maximize the financial returns of farming systems and to avoid contamination of the environment. This is of special concern to maize land in The Netherlands, since it has been used for manure disposal during more than 25 years. The decomposition rate of soil organic N was estimated from data of a long-term field experiment and used in a simulation model. Subsequently, the model was used to estimate the effects of Dutch manuring practice on maize land. The time course of the nitrogen (N) mineralization rate was estimated for three scenarios: i) following actual manure applications which have declined with time (A scenario); ii) assuming continuous applications in accordance with the present and anticipated legislation (P scenario); iii) assuming applications of 200 kg mineral fertilizer N ha^{-1} yr^{-1} only (M scenario).

We estimated that the actual mineralization rate (following the A scenario) in 1995 was 23–31 kg N ha^{-1} yr^{-1} higher than when manure had been applied at moderate rates (following the P scenario). Corresponding estimates for the year 2005 still amounted to 18–19 kg N ha^{-1} yr^{-1}. Our calculations suggest that it may be difficult to maintain soil organic N pools with mineral fertilizer only. Consequently, the mineralization rate following the M scenario decreased with time as did the yields of silage maize. The magnitude of the residual effect found in the present study, indicates that there is need and scope for fine tuning of N fertilizer recommendations. The simple model used in this paper seems a suitable tool to explore the magnitude of the residual effect of manuring.

Keywords: maize (*Zea mays* L.), manure, mineralization, nitrogen, residual effect, simulation, slurry

Introduction

From the early seventies, the area of forage maize on Dutch sandy soils increased spectacularly at the expense of other forage crops including grass (Anonymous, 1971–1996). Maize is mostly grown continuously because of its tolerance to a high cropping frequency.

A more than proportional share of the manure production on Dutch sandy soils, has been allocated to maize land for various reasons. One of the reasons is the insensitivity of the yield and quality of forage maize to heavy applications of manure (Schröder & Dilz, 1987).

Legislation on the timing and method of manure application was introduced in The Netherlands in 1987. In addition, upper boundaries were set to manure application rates. Legislation was initially extremely mild, especially for farmers growing maize, as, until recently, higher application rates were permitted on maize land than on all other arable land and grassland. The upper limits of the application rates on maize land were gradually reduced from circa 860 kg cattle slurry nitrogen (N) or 590 kg pig slurry-N ha^{-1} yr^{-1} in 1987 to circa 240 kg cattle slurry-N or 180 kg pig slurry-N ha^{-1} yr^{-1} in 1996 (Goossensen & Meeuwissen, 1990). Hence, permitted N-inputs via slurries have exceeded the N uptake potential of maize for many years.

Manuring practices are reflected in higher nitrate concentrations in the upper groundwater under maize land than under grassland, as indicated by a survey in 1993 (Van Swinderen *et al.* ,1996). However, the N surplus is not fully lost from the system as N is partly stored in soil organic matter. This material is decomposed in time periods varying from months to decades (Lund & Doss, 1980; Magdoff & Amadon, 1980; Sommerfeldt *et al.*, 1988; Liang & Mackenzie, 1992). Sooner or later, organic matter will mineralize and pose a threat to the environment if the N release is disregarded in the nutrient management (Görlitz *et al.*, 1985; Werner *et al.*, 1985; Dilz *et al.*, 1990; Schröder *et al.*, 1997b). Therefore, accurate quantification of the residual N effect of manuring is needed to adjust fertilizer N inputs to crop requirements. Quantification is also indispensable for a correct interpretation of the short-term effects observed in experiments, in terms of the long-term consequences. Without such knowledge, fertilizer management strategies may lead to an undesired accumulation or depletion of nutrient reserves in the soil. Motavalli *et al.* (1992), for instance, showed that the N requirements of maize are strongly influenced by the N rates applied in previous years. It is very likely that this holds also for maize land in The Netherlands, given the excessive application of manure in the past. Experimental data on the N contribution from manure applied to maize land for more than 25 years, to crop N supply are not available. Hence, the magnitude of effects can only be explored via simulation studies. An example of such a study was recently reported by Whitmore & Schröder (1996). They used a relatively complex model describing carbon (C) transformations next to N transformations. The model requires a relatively extensive data input, including weather and soil data, which may limit its applicability. Wolf *et al.* (1989) developed a much simpler soil organic N model. The limited data requirement of their model makes it reasonably easy to find complete data sets for its validation, as illustrated by Wolf & Van Keulen (1989). The model also satisfactorily predicted the N requirements of maize, as observed in field experiments and appeared suitable to make long-term projections of the N requirements of tropical maize (Osmond *et al.*, 1992). We decided to test the suitability of this simple model of Wolf *et al.* (1989) to predict the N mineralization in soils having received different amounts of manure for a large number of years.

Subsequently, the model was used to evaluate the Dutch manuring practice on maize land of dairy farms, in terms of N mineralization, N uptake and N losses.

Materials and methods

Experimental set-up

The decomposition rate of manure, needed to run the model of Wolf *et al.* (1989), was estimated from data of a long-term experiment on a sandy soil in Maarheeze, the Netherlands, carried out from 1974–1983. In this experiment, cattle slurry was applied in all years, but 1983, at rates ranging from 50 to 300 m^3 ha^{-1} yr^{-1}. The lowest slurry application rate was supplemented by 90 kg ha^{-1} yr^{-1} mineral fertilizer N from 1974 to 1979. Nutrient contents of the slurry were assessed at each application date and averaged 5.1 kg N, 1.0 kg phosphorus (P) and 4.6 kg potash (K) m^{-3} slurry. Slurry rates were registered, using a tractor-pulled precision applicator especially developed for field trials. Data on N-inputs via atmospheric deposition were derived from Erisman & Heij (1991) and Bleeker *et al.*(1993).

Silage maize was grown in the years 1974–1982 and its N-uptake was assessed annually by measuring dry matter yields (total above-ground mass) and N (Kjeldahl) contents. Total soil N (Kjeldahl), soil mineral N (by extraction with 1 *N* KCl) and soil organic matter (by loss on ignition) contents were determined per treatment to a depth of 60 cm, in the autumns of 1975, 1981 and 1982. Total N-contents were used to calculate the size of the N-pool (kg ha^{-1}) by multiplying with a C-content dependent bulk density (Whitmore *et al.*, 1992) for which we assumed an average C-content of the organic matter of 0.45 kg kg^{-1}. Organic N was defined as the difference between total soil N and mineral soil N. Over-winter N leaching was calculated as the integral of the product of mineral N concentrations (measured with ceramic cups installed at 100 cm depth) and precipitation surplus, from 1977–1978 to 1981–1982.

In the last year of the experiment (1983), Italian ryegrass was grown on the total experimental area to determine the residual N effect of the slurry, with split mineral fertilizer N rates (0, 160, 320, 480 kg N ha^{-1}) superimposed on all former slurry treatments. Grass was planted on March 15 and cut five times during the season. N-uptake in the grass was assessed at each harvest date. Details of the experiment are given in Schröder (1985) and Schröder & Dilz (1987).

Model description

In their model, Wolf *et al.* (1989) distinguish a labile (LON) and a stable (SON) soil organic N pool. Inputs, such as mineral fertilizer (NFER), manure (NSLURRY) and deposition (NRAIN) are partitioned to crop uptake, aggregated losses (leaching, denitrification, volatilization) and LON. SON is transferred to LON from which mineralized N is partitioned among crop uptake, losses and SON. We adopted a transfer coefficient from LON to SON of 0.15 and a ratio between the time constant of conversion of SON (TCS) and the time constant of conversion of LON (TCL) of 20 (Wolf *et al.* 1989). This implies that in an equilibrium situation SON is 3 times larger than LON (viz.: 3 / 0.15 = 20). TCL is best derived from the crop N-uptake of a control plot without fertilizer (Wolf *et al.*, 1989), as present in the Maarheeze experiment in 1983.

The transfer coefficients used for the years that maize was grown are given in Table 1. Relatively little N from manure (NSLURRY) is transferred to LON because about 65% of the N in slurries is almost directly available in inorganic form (Van Dijk & Sturm, 1983). However, only a small fraction of NSLURRY is taken up by the crop as we surmise that 25% (i.e. half of the NH_3-N) volatilizes. Fifteen percent of the fertilizer N is allocated to LON (stubbles, roots, exudates). The transfer coefficients for NFER and non-volatilized NSLURRY are based on Schröder & Dilz (1987) and Schröder *et al.* (1993). A relatively large part of NRAIN is allocated to losses, since it is almost fully inorganic and since 40% of the annual deposition takes place outside the maize growing season (Asman, 1992).

Slightly different transfer coefficients are used for the year in which grass was grown. The apparent N recoveries of fertilizer N were about 70% for all N rates and on all former slurry treatments (individual data not presented here). Therefore, we assumed that of the N mineralized from LON, 80% was taken up by the crop, 5% was lost and 15% was transferred to SON. We increased the fraction of NRAIN taken up by the grass to 50%, because the growing season of grass is longer than that of maize and a higher fraction is taken up by the crop, similarly to fertilizer N. Subsequently, TCL is calculated according to (Wolf *et al.*, 1989):

$$\text{TCL}, yr = ((\text{organic N in 0–60 cm soil layer}, kg\ ha^{-1}) / (\text{SON/LON ratio} + 1)) / ((\text{N-uptake of unfertilized grass}, kg\ ha^{-1} yr^{-1} - (\text{NRAIN}, kg\ ha^{-1} yr^{-1} \times 0.50)) / 0.80) \quad (1)$$

Goodness of fit between observed and simulated values was evaluated with the indices proposed by Addiscott & Whitmore (1987).

Table 1. Transfer coefficients for N from slurry (NSLURRY), mineral fertilizer (NFER), deposition (NRAIN), labile organic soil N pool (LON) and stable organic N pool (SON), used in modelling the maize experiment in Maarheeze (1976–1982) and the scenarios.

Source	Sink			
	Crop	Loss	LON	SON
NSLURRY	0.20–0.30*	0.50–0.40**	0.30	–
NFER	0.45	0.40	0.15	–
NRAIN	0.30	0.60	0.10	–
LON	0.425	0.425	–	0.15
SON	–	–	1.00	–

* gradually increased from 0.20 in 1979 to 0.30 in 1988 in the actual scenario
** gradually reduced from 0.50 in 1979 to 0.40 in 1988 in the actual scenario

Actual use of manure and fertilizers

Records of the amounts of manure applied to maize land over the last 25 years are not available and, hence, amounts had to be estimated to run the model. We confined ourself to the maize land of dairy farmers in the provinces Overijssel, Gelderland and Brabant. These three provinces comprise 70–90% of the national maize area (Anonymous, 1971–1996).

The fraction of the maize area in these regions allocated to dairy farms, on which grass and maize are practically the only crops grown, was based on statistical information for the 1986-1996 period (Anonymous, 1987; 1991; 1996). It increased from 0.65 in 1986 to 0.79 in 1995. For the 1970–1985 period the value of 0.65 was adopted. The remaining fraction of the maize area in these regions belongs to pig breeders and arable farmers.

Manure production on dairy farms was calculated from statistical information on stocking rates for the 1970–1995 period (Anonymous, 1987; 1996). One dairy cow, including off-spring, was assumed to produce 28.5 m^3 yr^{-1} slurry, the most common manure type on dairy farms (Anonymous, 1985). We surmised that 65% of the slurry is collected indoors and, hence, available for application to either grassland or maize land. Information on the allocation of slurry to maize land and grassland within dairy farms could not be deduced from statistical information. Instead, the allocation was based on expert knowledge from local extension officers. We assumed that of the available slurry 25 m^3 slurry ha^{-1} yr^{-1} was applied to grassland and the remainder to the maize land with a minimum of 50 m^3 ha^{-1} yr^{-1}. Calculated rates were never conflicting with the phosphorus (P) oriented upper boundaries set by the legislation from 1987 nor by the permitted P surplus (= input with manure and mineral fertilizer minus output with crop produce) that is to be introduced via legislation from 1998. We assumed a gradual increase of the N/P ratio in cattle slurry from 5.6 in 1987 to 6.3 in 1996 (Anonymous, 1985; Beijer & Westhoek, 1996). For later years we adopted the value of 6.3.

We assumed that manure was supplemented by mineral fertilizer N. Estimates had to be made, as accurate records are lacking. We assumed that until 1975 routinely 200 kg fertilizer N ha^{-1} yr^{-1} was applied. Between 1976 and 1990 N available from manure was gradually taken into account in the N requirements and replaced part of the mineral fertilizer N-input. We supposed that by 1990 55% of the total N-input from manure was accounted for. However, information from local extension officers made us surmise that 30 kg starter fertilizer N ha^{-1} was applied anyhow, irrespective of the N-input through manure. From 2002, calculated N rates exceeded the permitted N surplus (= input with manure and mineral fertilizer minus output with crop produce) according to the anticipated legislation. To comply with the legislation we reduced the mineral fertilizer N rate from 65 to 60 kg ha^{-1} for the 2002–2004 period and from 65 to 45 kg N ha^{-1} for the year 2005.

Table 2 summarizes our estimates of the time course of manure and mineral fertilizer N application in steps of five years. Scattered information from occasional surveys among maize growers provides confidence in these estimates (Table 3).

Table 2. Estimated actual slurry rates (m^3 ha^{-1} yr^{-1}) and N inputs with slurry and mineral fertilizer (kg N ha^{-1} yr^{-1}) on maize land of dairy farms (A scenario).

		Year							
		1970	1975	1980	1985	1990	1995	2000	2005
Slurry	Rate	50	50	74	74	50	50	50	50
	N input	220	220	326	326	230	240	245	245
Fertilizer	N input	200	192	133	30	73	68	65	45
TOTAL*	N input	420	412	459	356	303	308	310	290

* exclusive atmospheric N deposition

Table 3. Comparison of the estimated actual use of slurry (m^3 ha^{-1} yr^{-1}) and mineral fertilizer N (kg ha^{-1} yr^{-1}) inputs on maize land of dairy farms (A scenario) and the inputs recorded in surveys among maize growers ((n) = number of maize fields included in the survey).

Year	Estimated actual use		Survey			
	Slurry	Mineral-N	Slurry	Mineral-N	(n)	Source of survey
1977	117	147	77	122	(105)	Ten Hag (PAGV, 1996, pers. comm.)
1981	111	83	103	155	(104)	Anonymous (1981)
1982	109	68	114	117	(54)	Boer (1984)
1981-1989	93	–	79	–	(24)	Den Boer (NMI, 1996, pers. comm.)
1994	50	–	43	–	(10)	Den Boer (NMI, 1996, pers. comm.)
average	*96*	*99*	*83*	*131*		

Scenarios

The time course (1970–2005) of soil organic N and mineralized N on maize land were simulated for three scenarios: i) following the actual manure applications, as defined in the previous section (A scenario); ii) assuming not more than 39 kg manure-P ha^{-1} yr^{-1} having been applied in accordance with present and anticipated legislation (P scenario); iii) assuming applications of 200 kg mineral fertilizer N ha^{-1} yr^{-1} only (M scenario). The initial store of organic soil N was set to 6000 kg ha^{-1}.

N-inputs via atmospheric deposition were derived from national data given by Erisman & Heij (1991) and Bleeker *et al.* (1993). Deposition estimates ranged from 38 kg ha^{-1} yr^{-1} in 1995 to 52 kg ha^{-1} yr^{-1} in 1984.

We used the transfer coefficients given in Table 1. In the course of time, manure management has changed to application in spring, followed by immediate incorporation, due to legislation and farmers' awareness of the environmental impact. To mimic this change in technology in the A scenario, we gradually increased the fractions transferred to the crop from 0.20 in 1979 to 0.30 in 1988 with an associated reduction in losses.

For the P scenario we adopted constant N and P concentrations in the manure (similar to the ones used from 1996 onwards in the A scenario) and used the transfer coefficients arrived at in 1988 in the A scenario, throughout the entire period.

The model was applied for the three scenarios. The difference between the A and P scenario serves as an indicator for the additional mineralization resulting from excessive manure applications. The difference between the P and M scenario reflects mineralization resulting from moderate use of manure. Additionally, the long-term consequences of the three scenarios for N-uptake of maize and aggregated N-losses are explored. For this part of our study we assumed that 180 kg N ha^{-1} yr^{-1} were taken up at most by a maize crop. This value is slightly lower than the uptakes commonly observed in field experiments. Such a downward correction was considered necessary by us when maize is grown under practical conditions. If the sum of N allocations to the crop exceeded 180 kg N ha^{-1} yr^{-1}, the excess was allocated to losses.

Sensitivity analysis

An upper and a lower value for TCL was used in our calculations of the organic N pool dynamics and mineralization to determine its effect on the outcome of our study. In addition to this, we made an estimate of the relative contributions of the initial organic matter pool and of the additional pools originating from slurry-inputs and from mineral fertilizer inputs to the simulated N mineralization. We also explored the effect of LON/SON ratio on the simulated N mineralization by changing the ratio from 3 to 4.5 (Wolf *et al.*, 1989).

Results

Observed and calculated size of the soil N pool

Cumulative slurry applications to maize land increased the soil organic N pool in the Maarheeze experiment. A considerably smaller annual increase of the N pool was found when the calculated change from 1975, was based on the measurements made in 1981 than when it was based on the measurements made in 1982 (Figure 1). Because of this variation and inconsistencies of the response, we decided to base our further calculations on the estimated annual increase derived from regression analysis of the pooled data.

Only a part of the excess slurry N was stored in the soil, as indicated by balance sheet calculations of the N-inputs and N-outputs (Table 4). The surplus may indicate how much N was lost through volatilization of NH_3-N and denitrification.

N-uptake of the grass grown in 1983, was positively related to the size of the N pool, as determined in the autumn of 1982 (Table 5). TCL's calculated according to equation 1, decreased from 38 yr in the 50 m^3 ha^{-1} treatment to 16 yr in the 300 m^3 ha^{-1} treatment, suggesting a higher decomposition rate when inputs were high. The calculated values of TCL for slurry rates corresponding to the rates of our scenarios,

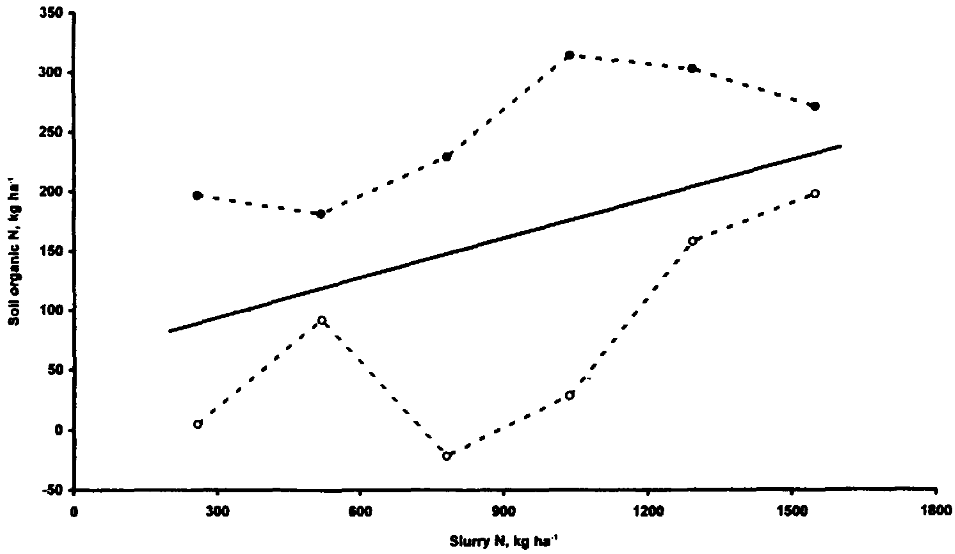

Figure 1. Average annual increase of soil organic N (kg $ha^{-1}yr^{-1}$) as related to annual N inputs with cattle slurry (kg $ha^{-1}yr^{-1}$) based on changes of the soil organic N pool between 1975 and 1981 (O) and on changes between 1975 and 1982 (●) and fitted annual increase of pooled data (—) after repeated cattle slurry applications on a sandy soil in Maarheeze continuously cropped with forage maize.

Table 4. Balance sheet of N-inputs, outputs and aggregated losses (kg ha^{-1} yr^{-1}) in the slurry experiment in Maarheeze (1976–1982).

		Slurry rate (m^3 ha^{-1} yr^{-1})					
		50	100	150	200	250	300
Inputs (I)	Slurry	258	519	781	1036	1292	1548
	Mineral fertilizer*	51	0	0	0	0	0
	Deposition	62	62	62	62	62	62
	TOTAL	371	581	843	1098	1354	1610
Outputs (O)	Crop uptake	137	159	177	199	195	198
	Leaching**	145	150	230	316	406	430
	Accumulation in soil***	89	118	147	175	203	231
	TOTAL	371	427	554	690	804	859
I - O	Surplus	0	154	289	408	550	751
Aggregated losses****		145	304	519	724	956	1181

* 90 kg N ha^{-1} yr^{-1} in 1976–1979, 0 kg in other years
** not assessed in first and last winter
*** based on regression analysis (Figure 1)
**** leaching + surplus

Table 5. Soil organic N pool in the autumn of 1982 (kg ha^{-1}, 0–60 cm) following the application of different slurry amounts between 1972 and 1982, the N-uptake (kg ha^{-1}) of unfertilized grass (5 cuts) in 1983 and the estimated time constant of conversion (TCL, yr) of the labile organic N pool (LON).

Slurry rate (m^3 ha^{-1} yr^{-1})	Organic N in soil (kg ha^{-1})	N-uptake of grass (kg ha^{-1})	TCL (yr)
50	8786	78	38
100	8698	85	33
150	9310	110	24
200	10121	136	19
250	9213	151	15
300	9246	146	16

fall within the range of 20–45 yr found by Wolf & Van Keulen (1989) in the experiments used for the validation of their model. Hence, we decided to use TCL's of 20 and 40 yr in our scenario study.

The mean difference between the observed and simulated size of the organic N pool was not significantly different from zero (Table 6), suggesting that systematic errors were small. The variation around the Y = X line (Figure 2), however, was considerable. This does not necessarily point at inappropriateness of the model, as the assessment of the soil organic N supply was associated with errors, also (Figure 1). Despite this mediocre goodness of fit between the observed and the simulated accumulation of soil organic N, we decided to proceed with the scenario study.

Scenarios

Model calculations with estimated data on actual N inputs indicate that the use of manure on maize land resulted in accumulation of soil organic N until about 1990 (Figure 3a, 3b). Obviously, accumulation was strongest when a low rate of decomposition was assumed, i.e. at a TCL of 40 yr. After 1995 the organic N pool increased slightly at a TCL of 40 yr, whereas it gradually decreased at a TCL of 20 yr. In the mineral fertilizer scenario, the organic N pool was about constant at a TCL of 40 yr, whereas a gradual depletion was calculated at a TCL of 20 yr. Since inputs of

Table 6. Statistical indices for the goodness of fit between the observed and simulated size of the soil organic N pool (kg ha^{-1}, 0–60 cm) for time constants of conversion of the labile N pool (TCL) of 20 and 40 years.

	M [a]	SE_M [b]	r [c]	±500 [d]	±1000 [d]	Number of observations
TCL = 20 yr	47	234	0.48	33%	83%	12
TCL = 40 yr	–359	237	0.50	50%	67%	12

a Mean difference between observed and simulated values
b Standard error of the mean difference
c Correlation coefficient
d Simulations within ±500 or ±1000 kg N ha^{-1} of the corresponding observations

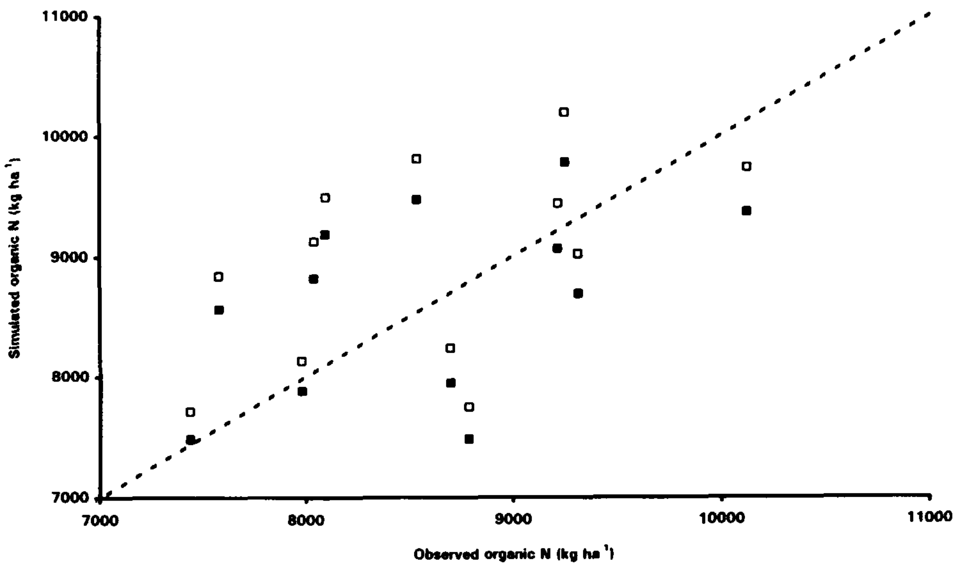

Figure 2. Observed versus simulated size of the soil organic N pool (kg ha^{-1}) after 6 (between 1975 and 1981) and 7 (between 1975 and 1982) annual applications of cattle slurry on a sandy soil continuously cropped with forage maize with a time constant of conversion of labile organic N (TCL) of 20 (■) and 40 (□) years. (---- = 'Y = X' line).

manure after 1996 are similar in the A and the P scenario, pool sizes of these two scenarios appear to converge towards values of about 7500 and 6500 kg ha^{-1} for TCL's of 40 and 20 yr, respectively.

The use of manure lead to a considerable increase in mineralization rate which was largest at a TCL of 20 yr. The calculated difference in mineralization rate among the various scenarios peaked around 1990 but persisted until the final years of our scenario study, especially at a TCL of 40 yr, as illustrated in Figure 4.

At a TCL of 20 yr, we calculated a difference in annual mineralization rate between the A and the P scenario of 31 and 19 kg N ha^{-1} in 1995 and 2005, respectively (Table 7). The corresponding values for a TCL of 40 yr were 23 and 18 kg N ha^{-1}. If mineral fertilizers had been the only source of N (M scenario), 25–39 kg N ha^{-1} less would have mineralized annually compared to the P scenario in 1995. In 2005 the difference between the M and the P scenario had increased to 31–45 kg N ha^{-1}. The difference in mineralization rate between the two extremes (A and M scenario) amounts to 48–70 kg N ha^{-1} in 1995 and 49–64 kg N ha^{-1} in 2005.

As the size of the organic N pools in the A and P scenario will converge, so will calculated mineralization rates. A continued moderate use of manure eventually resulted in an annual mineralization rate of about 80 kg N ha^{-1} compared to about 40 kg N ha^{-1} when mineral fertilizers were the only source of N.

For the selected conditions application of 200 kg fertilizer-N ha^{-1} (M scenario) resulted in a N uptake of about 125 kg ha^{-1}. In both scenarios where manure was used, N uptake was higher, as illustrated for a TCL of 40 years in Figure 5. However,

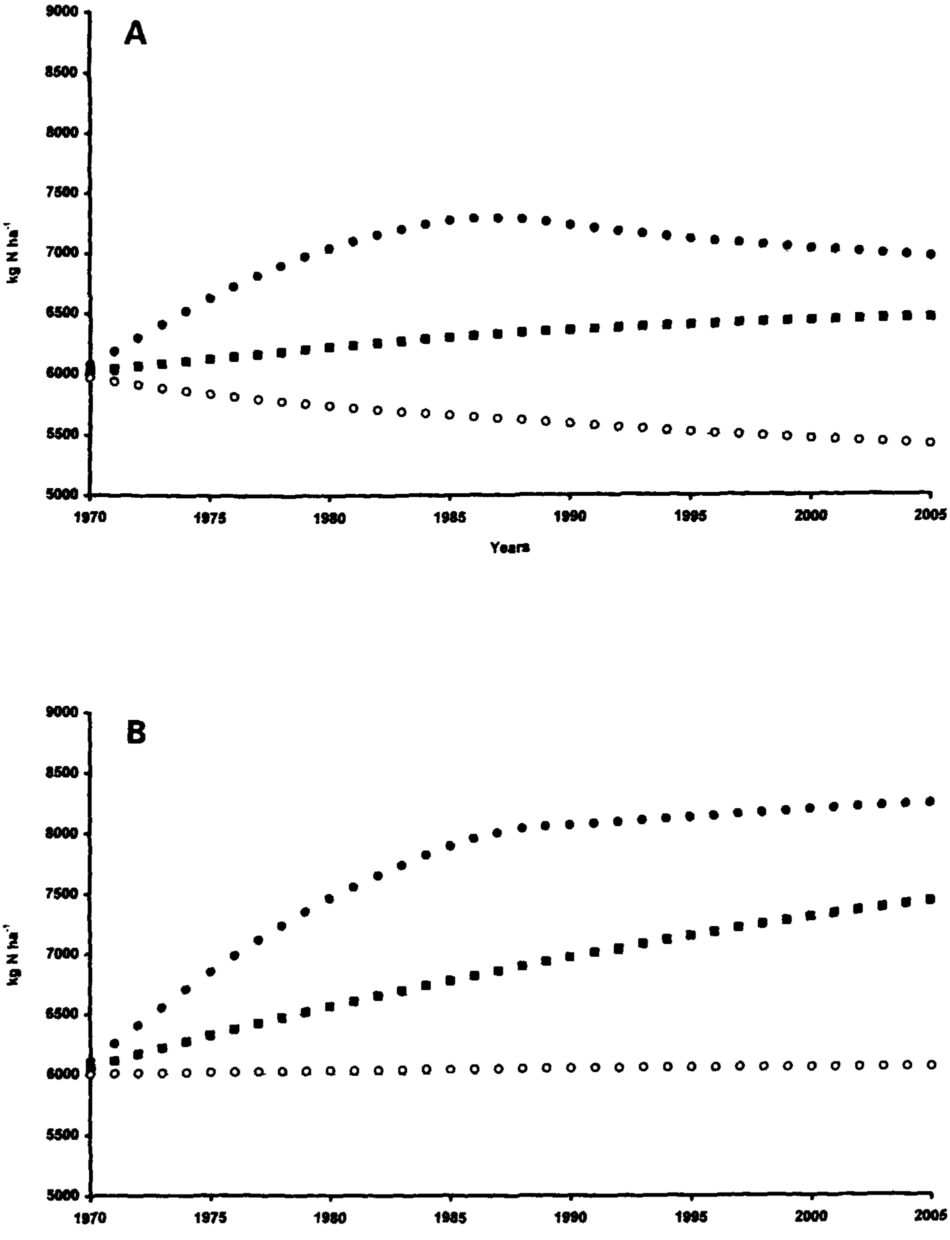

Figure 3. Size of the pool of soil organic N (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 20 (A) and 40 (B) years (● = actual use of manure, ■ = P-oriented use of manure, ○ = mineral N only).

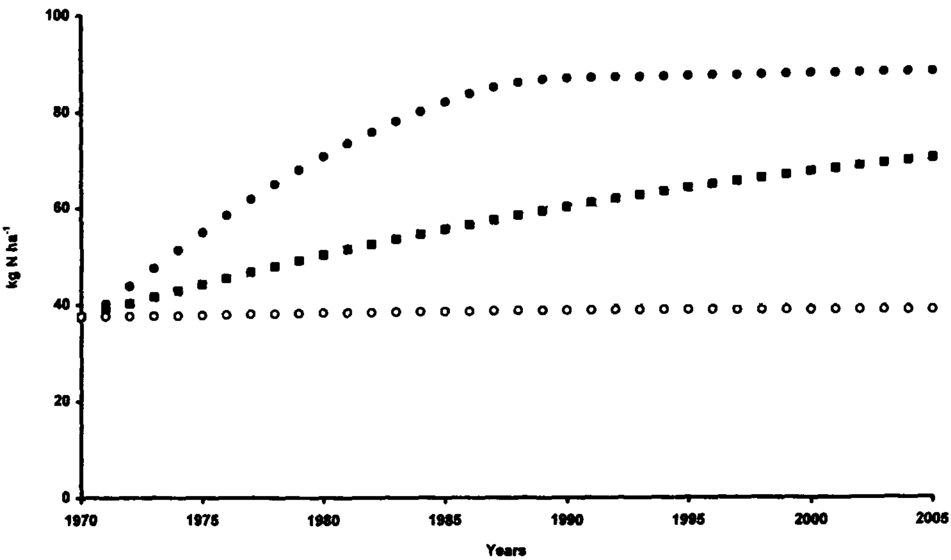

Figure 4. Annual mineralization of soil organic N (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 40 years (● = actual use of manure, ■ = P-oriented use of manure, ○ = mineral N only).

the predefined ceiling of N uptake (180 kg N ha^{-1}) was only attained in the actual scenario (A scenario) in the 1975–1985 period.

Calculated N losses in the A scenario were largest between 1975 and 1985, as manure inputs increased during those years and fertilizer N inputs were insufficiently adjusted to manure inputs. Before the introduction of legislation in 1987, ammonia volatilization contributed considerably to the losses, i.e. 23–49% of the difference in losses between the A and the M scenario was due to ammonia volatilization. After 1987, volatilization contributed only 15–19% to the difference in calculated losses. This is illustrated for a TCL of 40 years in Figure 6. In the long run, losses in the M

Table 7. Simulated difference between the N mineralization rate (kg ha^{-1}yr^{-1}) on actually manured maize land (A scenario) and on moderately manured maize land (P scenario) and between the N mineralization rate on moderately manured maize land and on maize land where only mineral fertilizers were used (M scenario), as a function of the time constant of conversion (TCL, years).

Contrast	TCL	Year							
		1970	1975	1980	1985	1990	1995	2000	2005
A - P	20	0	30	37	45	41	31	24	19
	40	0	11	21	27	27	23	20	18
P - M	20	0	13	22	28	34	39	42	45
	40	0	6	12	17	21	25	29	31

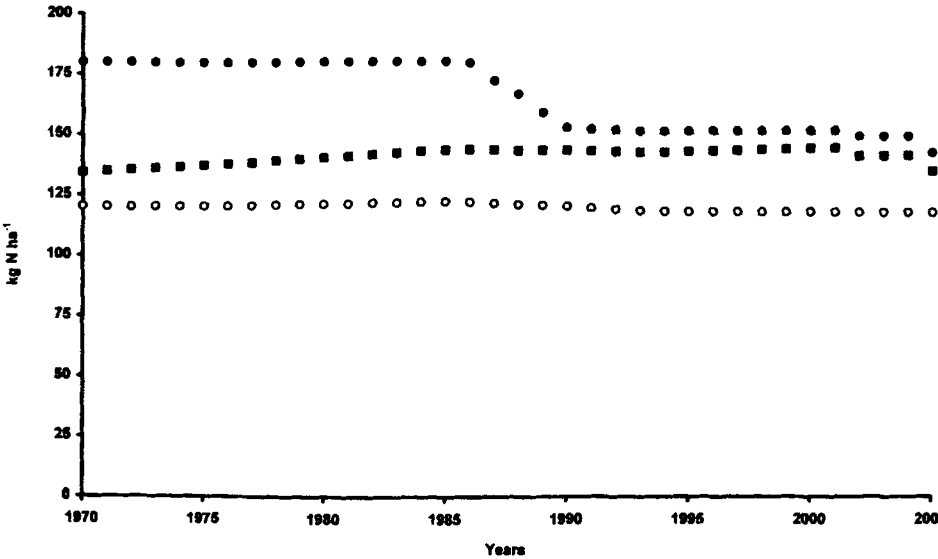

Figure 5. N uptake of maize (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 40 years (● = actual use of manure, ■ = P-oriented use of manure, ○ = mineral N only).

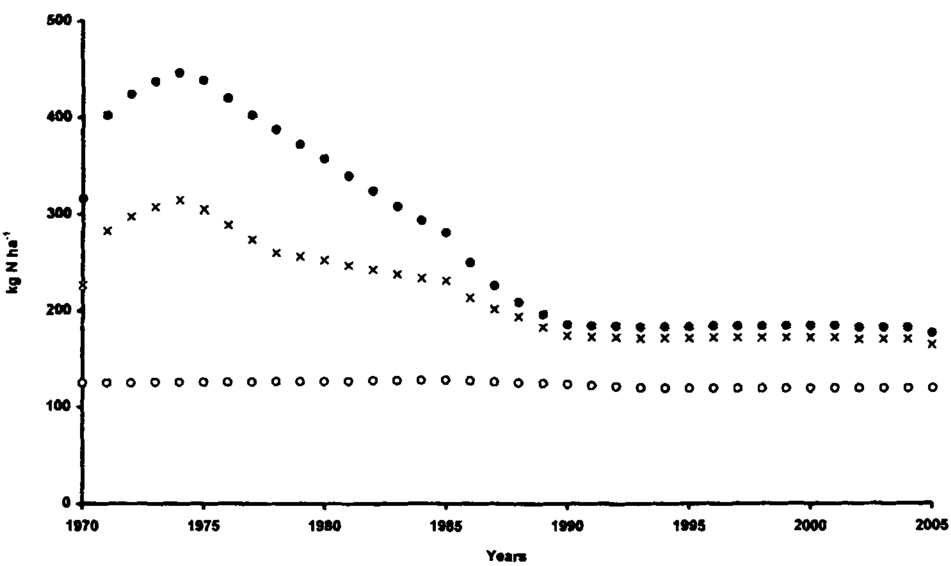

Figure 6. N loss (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 40 years (● = total loss inclusive NH_3-N loss with actual use of manure, **x** = total loss exclusive NH_3-N loss with actual use of manure, ○ = total loss with mineral fertilizer N only)

scenario are about 50 kg N ha^{-1} yr^{-1} lower than in the scenarios where manure is used (Table 8). This is mainly the result of the difference in size of the organic N pools and not because we assumed slightly larger losses from manure than from mineral fertilizer (Table 1). In 2005, the losses expressed per kg N uptake are about 0.2 kg smaller when mineral fertilizers are the only source of N (M scenario) than in the P scenario where manure and mineral fertilizers are combined. The long-term difference in N uptake between the M and the P scenario is in the order of 20 kg ha^{-1}, implying that of the observed difference in N losses between these two scenarios, 4 kg N ha^{-1}, resulted from the nature of the N source. The remaining difference resulted from the difference in pool size.

Sensitivity analysis

The choice of the TCL value had a notable effect on the magnitude of the residual N effect at different moments in time (Table 7). The contribution of the slurry-input to the simulated mineralization were much larger than the contribution from the initial soil organic matter pool or from the fertilizer-input (Table 8). This indicated that the calculated mineralization rates are more strongly affected by assumptions concerning the actual application rates of manure than by assumptions concerning the initial pool size. Runs of the model (separate data not presented here) indicated that a change of the initial pool size by 1000 kg N ha^{-1}, changed the mineralization rate by 3–4 kg N ha^{-1}, only. Changing the LON/SON ratio from 3 to 4.5 decreased the calculated mineralization rates by 6 kg N ha^{-1}. Contrasts between the three scenarios. were not affected, however.

Discussion

Nitrogen in manure is generally not fully available in the year of application because the release of organically bound N takes time. Continued use of manure will result in a gradual increase in the organic matter pool until, after many years, the annual

Table 8. Estimated contribution of the initial organic matter pool and of the additional pools originating from slurry-inputs and from mineral fertilizer inputs to the simulated N mineralization rate (kg $ha^{-1}yr^{-1}$) in 1995 on actually manured maize land (A scenario), on moderately manured maize land (P scenario) and on maize land where only mineral fertilizers were used (M scenario) with a TCL of 40 years and a LON/SON ratio of 3.

Contribution of:	Scenario:		
	A	P	M
Initial organic matter	23	23	23
Slurry-input	55	35	–
Fertilizer-input	7	5	14
Total	85	63	37

build-up of organic matter is in equilibrium with the annual decomposition. On the other hand, refraining from organic inputs may lead to a reduction in the organic matter pool. This may ultimately lower soil fertility. Knowledge of the relevant processes is needed for fine tuning of fertilizer recommendations and for a proper evaluation of the long-term effects of nutrient management strategies, as depletion and accumulation may have undesired effects on crop production and environment.

Residual N effects, as observed in a field experiment in which cattle slurry was applied at various rates for 9 consecutive years, were used to calibrate a model developed by Wolf *et al.* (1989). The difference between the N-inputs in the various treatments of this field experiment and the corresponding outputs, including N leaching and build-up of organic N, indicated how much N was lost through volatilization and denitrification. Only at the 50 m^3 slurry ha^{-1} yr^{-1} treatment, the surplus was nil, suggesting no other N losses than leaching. This seems unrealistic, so we may have underestimated one of the N-inputs or overestimated one of the N-outputs.

The N-uptake of an unfertilized grass crop, as observed in 1983, was positively related to build-up of organic N after application of cattle slurry in the previous 9 years. As on sandy soils residual mineral N in autumn is lost completely over-winter, except for an amount of circa 40 kg N ha^{-1} commonly present in spring in the upper 60 cm (Schröder *et al.*, 1997a), and winter rainfall between October 1982 and mid-March 1983 was 425 mm, we hypothesize that the observed difference in N-uptake largely resulted from mineralized N. The estimated time constants of conversion were 20–40 yr for the labile soil organic N pool (LON). This is equivalent to relative decomposition rates of 2.5%–5% yr^{-1} (viz.: 1/40 – 1/20) of LON. These values are within the range found by Wolf & Van Keulen (1989) in long-term experiments. When related to the total organic N pool (LON + SON), decomposition rates amounted to 0.7%–1.4%. The order of magnitude is in reasonable agreement with the findings of Kortleven (1963) who concluded that each year, 1.5%–2% of the 'active' humus (i.e. exclusive the inert fraction) decomposes.

The observed residual N effect in the experiment that we used to estimate the decomposition rate of the soil organic N, is in fair agreement with the findings of Görlitz *et al.* (1985) and Dilz *et al.* (1990). From data reported by Görlitz *et al.* (1985) a residual effect equivalent to 2–4% of the annual N input with slurry after 4 years of application can be calculated as compared to 7% of the annual N input with slurry after 9 years of application in our experiment. Dilz *et al.* (1990) found a residual effect equivalent to 12-16% of the annual N input with farmyard manure after 11 years of application. The agreement between their results and ours becomes better when the residual effect is expressed as a percentage of the annual input of the resistant organic N ('Nr'), as defined by Sluijsmans & Kolenbrander (1977). The relative share of 'Nr' in farmyard manure and slurry is about 40% and 25%, respectively. Thus, we calculated a residual effect of 28% of the annual 'Nr' input in our experiment. The corresponding value in the experiment of Dilz *et al.* (1990) varied between 27% and 36%.

The results of our model are in good agreement with a simulation study by Whitmore & Schröder (1996). For the year 2005, they calculated a difference in mineralization rate between their A and M scenario of 55–60 N ha^{-1}. The corresponding value in the present study was 49–64 kg N ha^{-1}. It must be noted, however, that slightly different assumptions were used in the definition of the scenarios in both model studies. Averaged over the 1975–1995 period Whitmore & Schröder (1996) assumed slurry-N and mineral fertilizer-N inputs of 310 and 170 kg ha^{-1} yr^{-1} in their A scenario. Corresponding values in the present study were 400 and 90 kg ha^{-1} yr^{-1}. The analysis presented in Table 8 pointed out that estimates of the mineralization rate are notably affected by assumptions concerning the actual use of slurry and mineral fertilizer N.

The results of our scenario study indicate that maize fertilized at recommended rates, takes up considerably less N than the commonly observed amount of circa 180 kg N ha^{-1}. This means that maize production in our scenarios is often N-limited, especially when mineral fertilizer is the only source of N. The discrepancy between this outcome of our modeling and the utter confidence of farmers in todays recommendations, indicates that we may have been too pessimistic in our assumptions with respect to the effective contribution of atmospheric deposition, fertilizer or mineralization to crop uptake. However, the discrepancy may also reflect the need to better account for residual effects of N sources applied in previous years. After all, N recommendations are usually based on trials that have been carried out at fields that were amply manured in the years prior to experimentation. The simple model used in this paper seems a suitable tool to explore the magnitude of the associated residual effect.

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